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Hong Liu, G. Lu. Velocity shear-related ion upflow in the low-altitude ionosphere. *Annales Geophysicae*, 2004, 22 (4), pp.1149-1153. hal-00317291

HAL Id: hal-00317291

<https://hal.science/hal-00317291>

Submitted on 2 Apr 2004

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Velocity shear-related ion upflow in the low-altitude ionosphere

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Received: 1 February 2003 – Revised: 29 October 2003 – Accepted: 17 November 2003 – Published: 2 April 2004

Abstract. Strong ion upflows with field-aligned velocity above 1000 ms^{-1} were observed by the European Incoherent Scatter (EISCAT) UHF Radar at Tromsø, Norway in the day-side auroral region at heights between 500–600 km during the 15 May 1997 magnetic storm. Both the EISCAT observations and the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) simulation results show that this event occurred in a region with low Joule heating rate, but with strong velocity shear. During the same period, the electron density and temperature showed no sign of soft particle precipitation, which is consistent with the UVI images from the POLAR satellite, thus excluding possible ion energization through soft particle precipitation. Our simple calculation shows that the velocity shear can provide sufficient energy for the observed ion upflow, thus suggesting shear-driven instabilities as a possible heating mechanism.

Key words. Ionosphere, particle acceleration, magnetospheric physics

1 Introduction

Upward flowing ionospheric ions have been recognized as an important part of the ionosphere-magnetosphere coupling in recent years. They are observed at various magnetic local times and altitudes from a few hundred kilometers to several Earth radii (R_E), by both ground-based radars and satellites (Yau et al., 1985; Lockwood et al., 1985; Loranc et al., 1991; Liu et al., 2001; Fujii et al., 2002). Various mechanisms have been proposed for ion energization. Frictional heating, such as Joule heating, is often considered to be the energy source for ion upflows at F-region heights (Keating et al., 1990). But the distribution function sometimes reveals perpendicular ion heating that cannot be accounted for by frictional heating alone, thereby indicating the presence of wave heating via plasma instabilities (Whalen et al., 1991). Current-driven in-

stabilities (i.e. Buneman instability, ion cyclotron instability, and ion-acoustic instability) are considered to be important energy sources (Ungstrup et al., 1979; Forme et al., 1993). These mechanisms, however, generally cannot operate at altitudes below 1000 km (Forme et al., 1993; Ganguli et al., 1994). On the other hand, energization must take place at low altitudes if we are to explain the fluxes, energies, and composition of ion flows observed at high altitudes. Therefore, there is a real need for a low-altitude ion energization mechanism.

Soft particle precipitation has been recognized as another important source for ion energization at low altitudes. By using simultaneous EISCAT Svalbard Radar (ESR) and EISCAT VHF observations, Ogawa et al. (2000) found that ion upflows are associated with a significant anisotropy of the ion temperature, isotropic increases of the electron temperature, and soft particle precipitation. A good correlation between ion outflows and auroral precipitation has been reported recently by Tung et al. (2001) near the nightside polar cap boundary. Liu et al. (1995) demonstrated by using simulations that soft electron precipitation can rapidly enhance the F-region ionization and the electron temperature, leading to a strong upward plasma expansion.

Studies of velocity shear-driven instabilities suggest the existence of other mechanisms. Simulation of electrostatic turbulence due to sheared flows transverse to the magnetic field shows that velocity shears can lower the threshold values for the field-aligned current-driven instabilities to excite electrostatic waves, thus energizing ions at lower altitudes (Ganguli et al., 1988; Nishikawa et al., 1990). Romero et al. (1992) reported the occurrence of a coherent structure (vortex-like) of the electric field potential and significant resonant ion acceleration in the nonlinear evolution of lower hybrid instabilities. The growing waves are associated with small vortices in the linear stage, which evolves into a nonlinear state dominated by larger vortices with lower hybrid frequencies, becoming a potential source for ion heating.

Ion upflow associated with velocity shears has been reported in Hilat satellite observations in the cusp/cleft region

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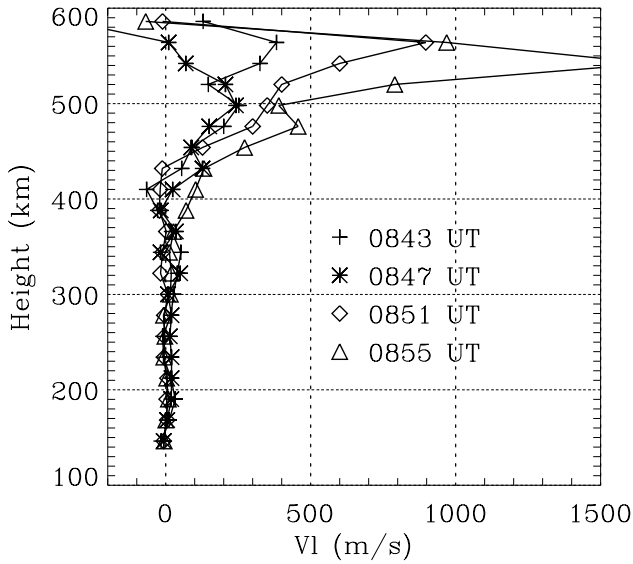


Fig. 1. The height profile of the field-aligned ion velocity at four consecutive times on 15 May 1997. Positive means upward.

at 800 km altitude (Tsunoda et al., 1989). To further examine the plausibility of the shear-related ion energization mechanism, we present a case study of a strong ion upflow observed by EISCAT radar at an altitude range between 500–600 km on 15 May 1997. Convection patterns derived from the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure show that this ion upflow occurred near a convection vortex where a strong velocity shear was observed. Calculation of the shear energy shows that it can provide sufficient energy for the observed ion upflows.

2 Radar Observations

The EISCAT Tromsø UHF radar is located at 69.7° N geog. (66° N geom.). Four parameters are routinely derived from the radar observations, namely, the electron density, the electron and ion temperature, and the line-of-sight ion velocity. The line-of-sight ion velocity measured approximately along the local geomagnetic field direction is generally referred to as the field-aligned ion velocity at F-region heights. The $\mathbf{E} \times \mathbf{B}$ drift velocity can be determined by a tri-station measurement. Detailed descriptions of the EISCAT radar system can be found in Rishbeth and van Eyken (1993).

The 15 May geomagnetic storm started at 01:59 UT with a storm sudden commencement. The D_{st} index reached a minimum of -120 nT at 12:00 UT, and the AE value was about 2000 nT at 12:35 UT. The ion upflow burst studied here occurred during 08:43–08:55 UT, which was during the main phase of the magnetic storm, with increasing duskward IMF B_y and relatively stable southward IMF B_z .

Figure 1 presents the height profile of the field-aligned ion velocity observed at four consecutive times. From 08:43 UT, the upward field-aligned ion velocity showed continuous increase at altitudes above 400 km. It reached more than

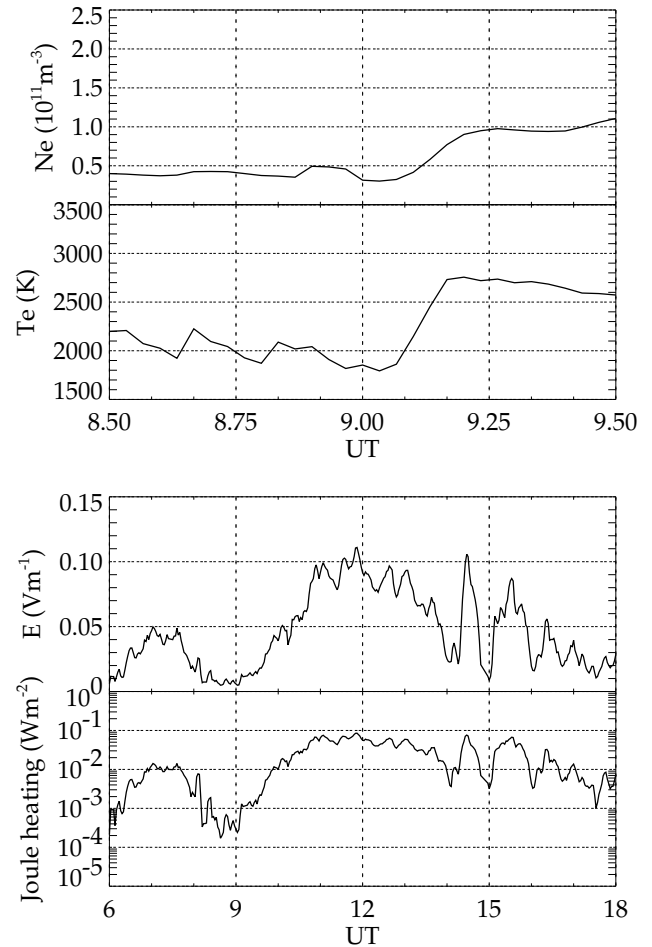


Fig. 2. The EISCAT measurements on 15 May 1997. The first and second panels show the electron density and temperature averaged between 350–600 km during 08:30–09:30 UT. The third and fourth panels show the electric field and the Joule heating during 06:00–18:00 UT. LT=UT+1 h; MLT=UT+2.4 h.

1000 ms^{-1} at 550 km altitude at 08:55 UT, which is very unusual at this altitude. The velocity dropped to values below 200 ms^{-1} afterwards. The electron density and temperature averaged over 350–600 km during 08:30–09:30 UT are shown in the first two panels of Fig. 2. They showed no sign of large enhancements before 09:00 UT, indicating the lack of soft particle precipitations (Millward et al., 1999). The Joule heating rate calculated from the EISCAT measurements (Davies et al., 1997) is shown in the bottom panel of Fig. 2. Note that the Joule heating rate dropped below 1 mW m^{-2} between 08:30–09:00 UT.

Figure 3 shows the clockdiagonal plot of the ion drift velocity perpendicular to the geomagnetic field measured by EISCAT. During the 24 h period, ion drifts at EISCAT experienced several changes. The drift speed was below 50 ms^{-1} between 00:00 and 07:00 LT (except for one outlier at $\sim 03:00$ LT, which is not of interest to this study), but reached more than 1500 ms^{-1} during 13:00–17:00 LT. A large velocity reversal occurred around 10:00 LT ($\sim 09:00$ UT) when the ion drift rotated from poleward to equatorward, coinciding with the strong ion upflows observed by EISCAT.

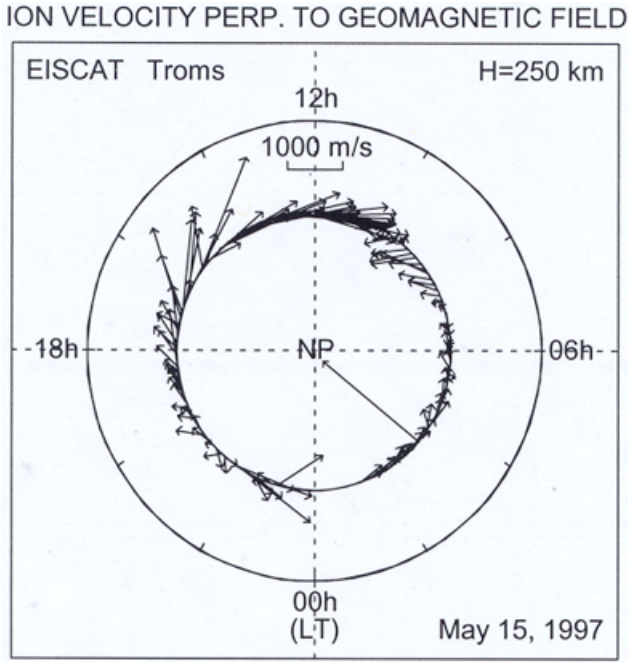


Fig. 3. The ion velocity perpendicular to the geomagnetic field observed by EISCAT. A significant reversal occurred around 10:00 LT. LT=UT+1 h.

3 AMIE Results

The AMIE technique is used to derive the snapshots of large-scale ionospheric convection patterns and other electrodynamic parameters, such as field-aligned currents (Richmond and Kamide, 1988). Data inputs for this particular event include a global network of ground magnetometers (121 in total), the SuperDARN radars, and global auroral images from the Polar UVI (see Lu et al. (1998) for more details and references). Figure 4 shows the convection patterns derived from AMIE for the period of 08:40–09:05 UT on 15 May 1997. One can see that the EISCAT radar (represented by the letter “E” on the convection maps) was located near the center of a convection vortex at about 11:00 MLT, which later merged with the duskside convection cell. This is fully consistent with the convection velocity measurements from EISCAT shown in Figure 3. We should note that during this time interval two of the SuperDARN radars in Pykkvibaer and Hankasalmi did not obtain sufficient back scatters over the Tromsø region. The small convection vortex shown in the AMIE convection maps was determined mainly by ground magnetometers over the Scandinavian region, along with ionospheric conductances derived from global auroral images. The AMIE results also show that the convection vortex is associated with upward field-aligned currents, with a maximum current density of $\sim 1.0 \mu\text{A m}^{-2}$.

4 Discussion

Three mechanisms have been proposed for ion energization at *F* region heights, namely, Joule heating, soft particle precipitation, and velocity shear. As shown in Fig. 2, the Joule

heating rate during the period of 08:30–09:00 UT was very low, actually close to the minimum value for the day. Therefore, it is unlikely to be the direct source for the observed up-flowing ions. The low electron density and temperature in the *F*-region indicated that no soft particle precipitation occurred during this period. This is further corroborated by the UVI images from the POLAR satellite, showing that EISCAT was located equatorward of a very faint dayside aurora at the time when the intense ion upflow was observed. These evidences thus exclude possible heating by soft particle precipitations.

Field-aligned current-driven instabilities have also been proposed to be a possible mechanism (Ungstrup et al., 1979; Satyanarayana et al., 1985; Forme et al., 1993). However, the maximum field-aligned current density derived from both the EISCAT observation (the divergence of the horizontal current) and the AMIE procedure during 08:30–09:00 UT was only about $1.0 \mu\text{A m}^{-2}$. This value is much lower than the approximate $20 \mu\text{A m}^{-2}$ threshold required to excite O^+ ion cyclotron waves at these altitudes (Satyanarayana et al., 1985). Therefore, the field-aligned current-driven instabilities cannot be directly invoked for the transverse heating in this case.

As mentioned in the Introduction, studies of velocity shear-driven instabilities have shed light on the existence of new mechanisms for ion energization at low altitudes. Ganguli et al. (1994) demonstrated theoretically that even a small amount of velocity shear in the transverse flow is sufficient to excite a large-scale Kelvin-Helmholtz mode, which can nonlinearly steepen and give rise to plasma waves in the range of ion cyclotron to lower hybrid frequencies. These waves are potential sources for ion heating (Walker et al., 1997; Amatucci et al., 1998). Another possibility is that the velocity shear can lower the threshold for field-aligned current-driven instabilities to excite ion cyclotron waves, thereby heating the ions at low altitudes (Nishikawa et al., 1990). According to Ganguli et al. (1994), the power density transferred by the instabilities to the O^+ ions from the convection flow is $P \approx 2.7 \times 10^{-4} \beta \omega \text{ J m}^{-2} \text{ s}^{-1}$. The growth rate (or frequency) of the instability ω is generally above 10^2 s^{-1} . And $\beta = \Delta V_i / V_i$, where V_i is the average velocity of the convective flows and ΔV_i is the average change of its velocity due to dissipation by instabilities. Taking the growth rate ω as low as $\sim 10^2 \text{ s}^{-1}$, we obtain $P \approx 2.7 \times 10^{-2} \beta \text{ J m}^{-2} \text{ s}^{-1}$. Assuming that any change in the convective velocity from its steady state value is restored to its original or a new steady-state value via instabilities, we roughly calculate ΔV_i as the product of the wave growth time ($\sim 10^{-2} \text{ s}$) and the average changing rate of the convective velocity ($\sim 2 \text{ m s}^{-2}$ from Fig. 3). This yields an estimate of ΔV_i to be $2 \times 10^{-2} \text{ m s}^{-1}$. Taking the average V_i during 08:40–09:00 UT as 500 m s^{-1} , we then obtain the value of $\sim 4 \times 10^{-5}$ for β during the corresponding period. Therefore, we have $P \approx 1.1 \times 10^{-6} \text{ J m}^{-2} \text{ s}^{-1}$. This is more than ten times higher than the power density needed for accelerating the observed upflowing ions, which is approximately $8.4 \times 10^{-8} \text{ J m}^{-2} \text{ s}^{-1}$ (taking the average ion density during 08:40–09:00 UT to be $\sim 5 \times 10^{10} \text{ m}^{-3}$ and the average field-aligned ion velocity to be $\sim 500 \text{ m s}^{-1}$). Therefore, the

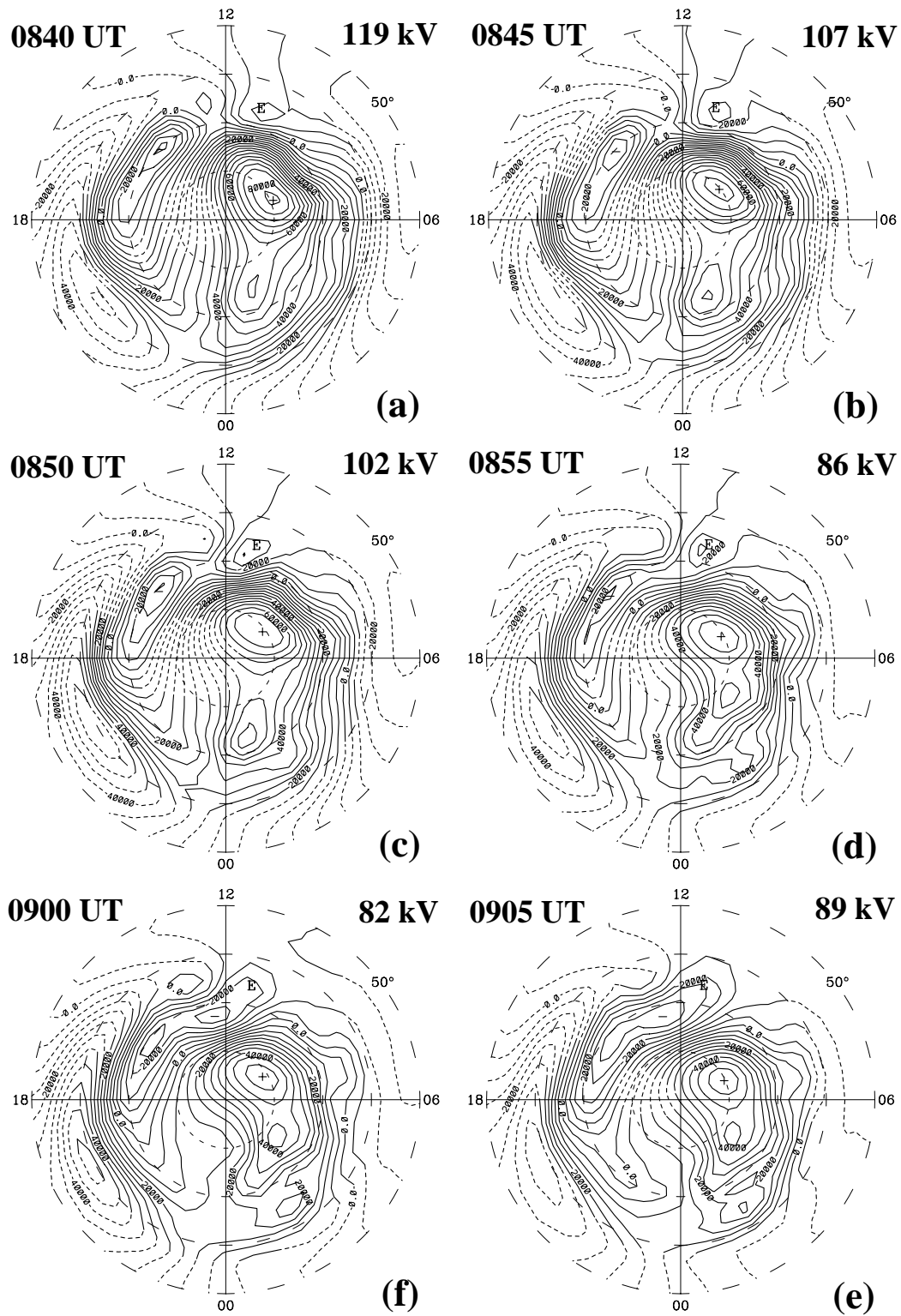


Fig. 4. Convection patterns on 15 May 1997 derived from AMIE. The letter “E” represents the location of EISCAT (near 11:00 MLT). The convection contours are shown as solid lines where the AMIE procedure infers an uncertainty in the large-scale electric field of less than 50%, and as dashed lines where the uncertainty exceeds 50%.

velocity shear was able to provide sufficient energy for the ion upflow burst during this event.

Velocity shear-related ion upflows have also been observed by other radars (i.e. Sondrestrom radar) at F-region heights (Semester et al., 2003). Similar analysis of energy involved in these events is expected to further elucidate the energization mechanism via velocity shear.

Acknowledgements. We thank S.-Y. Ma for helpful discussions. We are grateful to the director and staff of EISCAT for operating the facility and supplying the data. EISCAT is an international association supported by Finland (SA), France (CNRS), Germany (MPG), Japan (NIPR), Norway (NFR), Sweden (NFR), and the United Kingdom (PPARC). The operation of the SuperDARN radars in the Northern Hemisphere is supported by the national funding agencies of the US, Canada, and France. We are very grateful to M. Ruohoniemi at JHU/APL for preparing the radar data. The Polar UVI data was prepared and provided by D. Lummerzheim at University of Alaska at Fairbanks. Work at HAO/NCAR was supported by the NASA SEC Theory and Guest Investigator programs.

Topical Editor M. Lester thanks A. Yau for his work in evaluating this paper.

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